Three SPH Novel Benchmark Test Cases for free surface flows

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***Abstract*—Benchmark Test Cases have been used by SPHERIC interest group members for the validation of SPH models and their corresponding computer implementations. Since the use of SPHERIC benchmark test cases as validation reference for SPH implementations has slightly declined in the most recent editions, we think it might be interesting to document three novel test cases with the aim of enriching the database with complementary validation data. The first proposed test case is a wave impact problem in a rectangular tank. The time history of the motion of the tank and the pressure of the first instances of lateral and roof impacts for both water and oil are provided. An analysis of the two-dimensionality and repeatability of the pressure peaks is provided. The second proposed test case treats the coupling of the angular motion of a sloshing tank and a single degree of freedom structural system. Finally, the third proposed test case, is a canonical fluid structure interaction problem consisting in the interaction between a free surface sloshing flow and an elastic body. As both SPH practitioners and experimentalists, regardless of the discussion provided in this paper, we are committed to improving these test cases for future use. We hope to increase our experimental skills and capabilities not only in light of experience from our own simulations but mainly by receiving a feedback from the SPH community.**

I. Introduction

Benchmark Test Cases have been used by the SPH community for the validation of SPH models and their corresponding computer implementation. One of the aims of the SPHERIC Workshops, as stated in the preface of the 2008 SPHERIC Workshop proceedings book, is to define and run benchmark test cases. In 2008 Workshop, only two papers made use of the SPHERIC benchmark test cases in order to validate computations. In 2009, that figure was the same. It may be therefore interesting to provide some new test cases that could serve as basis for validation procedures as well as providing room for some competitiveness between the different codes. There is a specific space in the SPHERIC web site from where the information corresponding to those cases can be downloaded as well as an application form for proposing new test cases. Although it is possible to use such a procedure through the SPHERIC web site directly, we think it would be interesting for the SPH community to discuss the newly proposed benchmark cases in the open forum of the 2010 Workshop. This is the reason why we think it can be adequate to organize those materials as a proper paper.

One of the main interests of the authors in the past has been related with free surface flows [1] as well as with the interaction between free surface flows and solid mechanics, either in the field of ship motions [2] or in the field of solids deformations and fluid structure interactions [3]. The three new proposed test cases spring naturally from those interests since they incorporate a wave impact problem in a sloshing flow in a rectangular tank, the coupling of the angular motion of a sloshing tank and a single degree of freedom structural system and the interaction between a free surface sloshing flow and an elastic body.

The cases are canonical in the sense that we have tried to simplify them as much as possible, aiming at making them useful for validating the corresponding SPH computational models. Such simplicity is related to their two-dimensionality which is in-depth discussed for the first proposed benchmark. The three proposed cases incorporate, we believe, all the necessary information to implement them in SPH codes. They are presented and discussed in this paper but detailed information necessary for the implementation and posterior validation assessments is available from the following link: http://canal.etsin.upm.es/ftp/SPHERIC_BENCHMARKS/

II. Wave Impact problem

A. General

The first test case focuses on a wave impact problem, by providing time histories of the pressure recorded at specific locations, together with the corresponding roll angle history of the periodic angular motion of a sloshing tank. This test case is an improved version of the test presented in [1] which focused on lateral impact problems in a rectangular tank and that has been already taken as reference data for the validation of an ISPH code by Khayyer et al. [4]. In the present paper, significant improvements and contributions with respect to reference [1] are presented. First, the test case focus on what is expected to be the most deterministic impact event, which is the first pressure peak, for which a repeatability analysis is provided. Second, the influence of liquid viscosity

TABLE I
PHYSICAL PROPERTIES (UNITS SI) OF THE LIQUIDS: ρ FOR DENSITY, μ FOR THE DYNAMIC VISCOSITY, ν FOR THE KINEMATIC VISCOSITY, σ FOR SURFACE TENSION

	ρ	μ	ν	σ
Water	998	8.94e-4	8.96e-7	0.0728
Oil	900	0.045	5e-5	0.033
Glycerin	1261	0.934	7.4e-4	0.064

is considered by performing experiments not only with water but also with oil. Third, a higher sampling rate of the pressure register is used. Fourth, not only lateral but roof impacts have been considered. Finally, a study of the two-dimensionality of the problem has been carried out using the same model, but increasing its thickness.

We think all this may be sufficient to consider this benchmark case a valuable contribution to the test case data base where two other cases, 2 and 5, deal with similar topics. In the literature in general, a very significant contribution belongs to Lugni et al [5], who described the extraordinary accelerations during wave impact events, though their work is not specifically arranged so as to be useful as reference for CFD validation attempts. A widely known attempt to provide such validation data emerged from the Special 1st "Sloshing Dynamics" Symposium at ISOPE-2009 Conference, in which a benchmark test case was proposed to all participants [6]. Some contributions from the SPH community took place in this mini-symposium [7], [8]. Compared to that, the present test case provides a repeatability analysis focusing on the first impact in addition to an exact description of the tank motion and data for a larger fluid viscosity.

The tank used in the proposed wave impact benchmark test case is rectangular built with plexiglass. Its dimensions (mm) as well as the pressure sensor positions can be seen in figure 1. It is a scaled down longitudinal section of a LNG vessel tank. The dimension perpendicular to the paper (thickness hereinafter) can be changed by halving (0.5X cases) and doubling (2X) the dimension (1X=62mm) of the original tank. The sensors are placed exactly in the center plane of the tank in the thickness direction. The aim of these multiple configurations is to assess whether the data obtained from the experiments can be considered $2D$. The rotation center is at the center of the bottom side of the tank for this test case. The amplitude of the motion is 4 degrees. The liquids used in the experiments can be considered Newtonian at standard testing conditions and their physical properties are presented in table I (glycerin will not be considered for the wave impact case). If we define the Reynolds number from the liquid filling depth and the propagation velocity of an equivalent dam-break, a range of Re of approximately 100, 2000 and 100000 is covered with a similar Webber number for all the configurations (of the order of 1000). For further details on the experimental setup, we forward the reader to references [1], [9], [10].

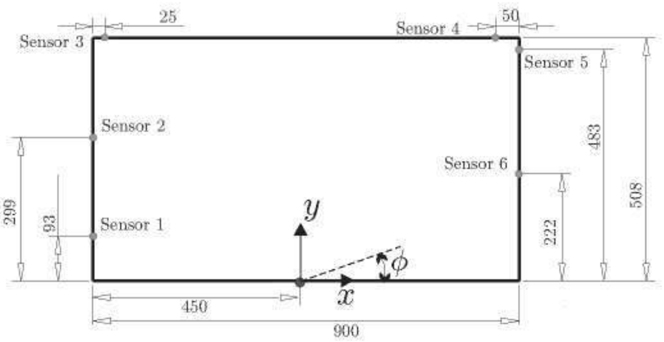


Fig. 1. Tank dimensions and sensor positions

B. Lateral impact with water

The liquid level for the lateral impact is $H = 93mm$, corresponding to sensor 1 in figure 1. The first sloshing period for this depth is calculated using the equation 1 ($L = 900mm$).

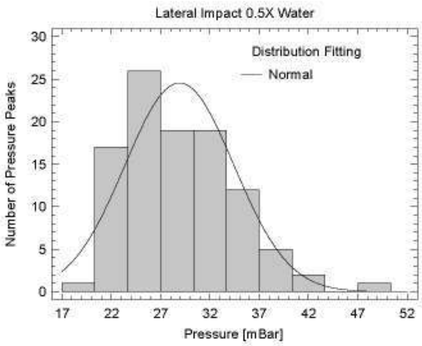
$$T_0 = 2\pi \left(\sqrt{\frac{\pi g}{L} \tanh\left(\frac{\pi H}{L}\right)} \right)^{-1} = 1.9171s \qquad (1)$$

The period of oscillation for this experiment is $0.85T_0 = 1.6295s$, which was found to be the period with the highest first pressure peak. For this filling ratio, overturning waves are generated that impact on the lateral wall of the tank, close to the still water level surface. The impact pressure events show a quite significant random behavior. For each of the cases considered in this paper, 100 experiments were run, leaving 3 minutes to allow the liquid come to rest between each run. The statistical distribution corresponding to the first peak could be in principle fitted with a normal. This can be seen for the three thicknesses in the lateral case (figure 2). A deeper study is necessary in these regards because in some of the cases, some criteria of normal fitting are not fulfilled. A detailed description of these registers can be found on the test cases web page.

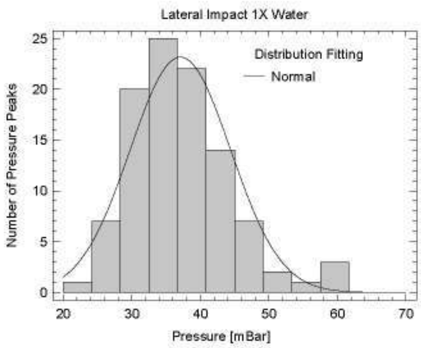
In figure 3, a sequence of images during to the first impact event for the range of different thickness (0.5X, 1X, 2X) tanks is found. The dynamics observed, obtained with a 300FPS high speed camera, in the three cases sequence is similar. Sensor 1 pressure and roll angle history were registered in all these experiments. Those presented in figure 4 have pressure peak closest to the mean peak of all 100 experiments. Regardless of the similar dynamics of the impact for the three tanks (0.5X, 1X, 2X), as shown in figure 3, the impact pressure mean value increases substantially with the tank thickness, which is quite disturbing. This is most noticeable looking at figure 4 and table II, where the mean and standard deviation of the 100 tests is shown for each case. Tests with thicker tanks will be conducted in the near future in order to assess whether a thickness independent $2D$ stable solution can be found.

C. Lateral impact oil

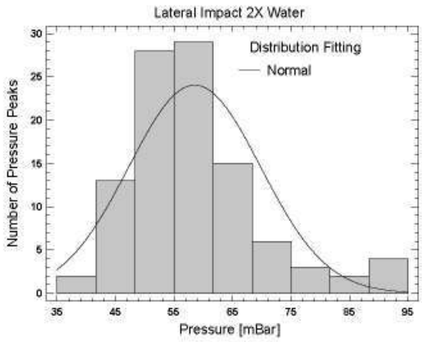
The mechanical properties of the oil used in the experiments are shown in table I. The dynamics differs from water



(a) 0.5x



(b) 1x



(c) 2x

Fig. 2. Lateral impact with water: First peak normal distribution fitting (100 samples)

TABLE II
STATISTICAL DISTRIBUTION OF LATERAL IMPACT PRESSURE PEAKS [mBar]

Test	Mean	ST Deviation	Pearson Coeff.
0.5x Water	28.91	5.52	19.09%
1x Water	37.10	7.32	19.72%
2x Water	58.53	11.28	19.27%
1x Oil	6.86	0.16	2.31%
2x Oil	16.94	0.25	1.48%

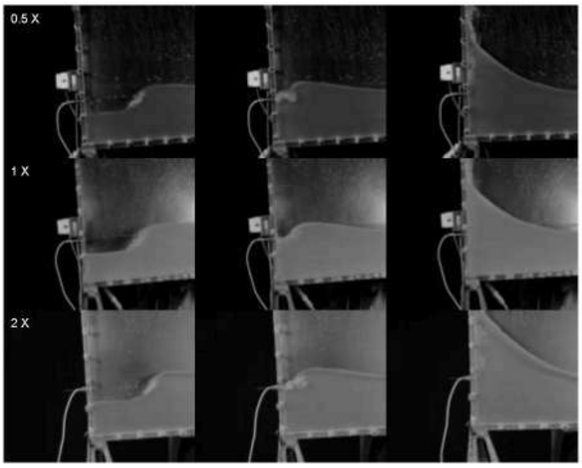


Fig. 3. Lateral impact with water: Free surface shape during first peak event

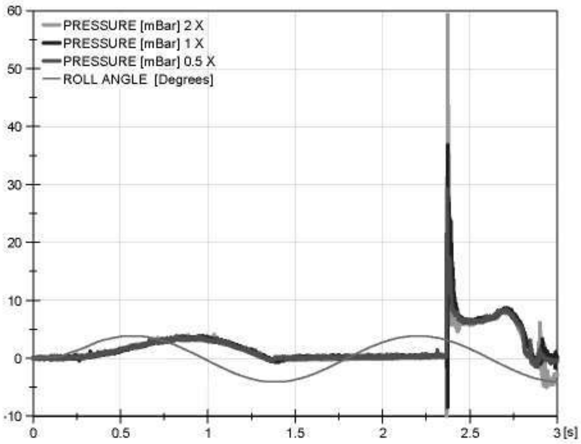
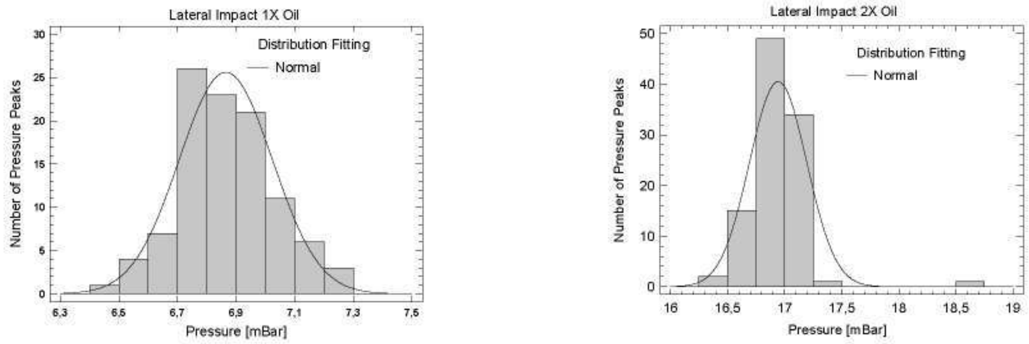


Fig. 4. Lateral impact with water: First peak pressure register

substantially, consistently with the drop in Reynolds number due to the increased kinematic viscosity and the corresponding thickening of the boundary layer. If we take a look at the selected pressure registers of figure 5 for the first impact event, it is noticeable that no impact actually takes place for 0.5X tank. In figure 6, a sequence of images corresponding to events during the impact is shown. A breaking event, though mild, occurs only for 2X case. Case 1X is particularly relevant because no 3D structures seem to onset which makes it a good candidate for a laminar 3D simulation. It is noticeable as well that the repeatability of the impact pressure values increases dramatically compared to the water case, as can be observed from the standard deviation and Pearson coefficient in table II (0.5X is missing for oil since no impact takes place), and from the histogram of those cases in figure 7.

D. Roof impact water

The roof impacts are quite relevant in the industry due to the tank roof being often less reinforced than the bottom part and hence subject of higher risks for same order impact pressure values. The liquid level for this set of experiments corresponds to a 70% fill ratio. The period of oscillation is the first sloshing period for this depth, i.e. $T_0 = 1.1676s$ and roof impacts are generated in each cycle. In this configuration neither overturning nor breaking waves are generated. It seems that air is not entrapped during the impact event and this could have a substantial influence on the pressure field [5]. This difference makes this case a distinct challenge compared to the lateral sloshing one, maybe more appropriate for monophasic



(a) 1x

(b) 2x

Fig. 7. Lateral impact with oil: First peak normal distribution fitting (100 samples)

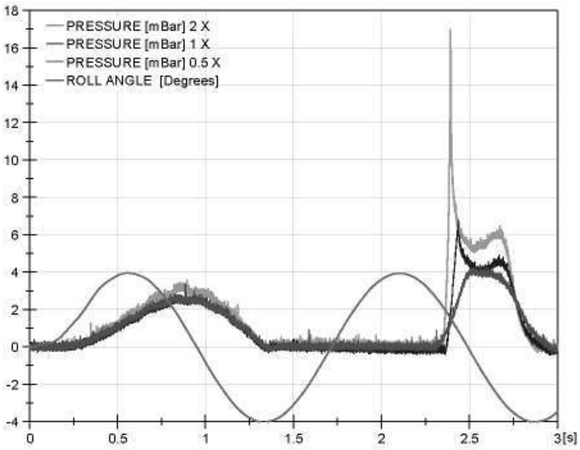


Fig. 5. Lateral impact with oil: First peak pressure register

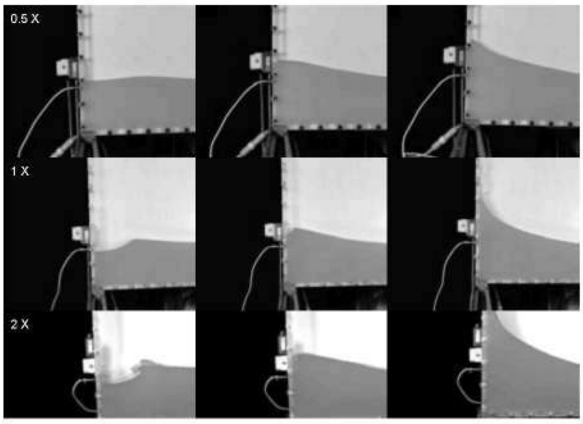


Fig. 6. Lateral impact with oil: Free surface shape during first peak event

TABLE III
STATISTICAL DISTRIBUTION OR ROOF IMPACT PRESSURE PEAKS

Test	Mean	ST Deviation	Pearson Coeff
0.5x Water	29.90	3.25	10.86%
1x Water	43.00	7.99	18.58%
2x Water	55.75	6.98	12.52%
1x Oil	20.18	2.34	11.57%
2x Oil	19.17	2.50	13.04%

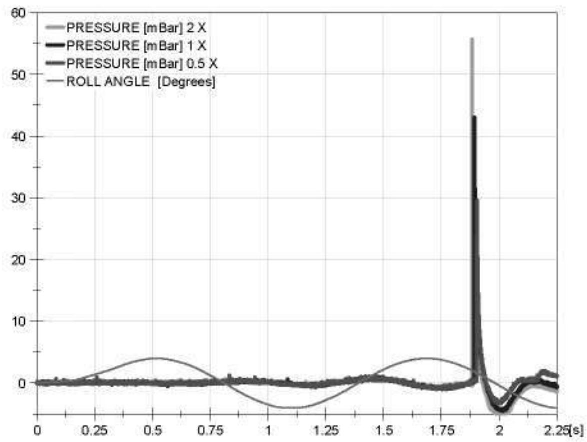


Fig. 8. Roof impact with water: First peak pressure register

models. A sequence of images during the first impact event for the range of different thickness (0.5X, 1X, 2X) tanks is shown in figure 9. The general dynamics seems similar for the three configurations. Likewise the lateral impacts, 100 experiments were run, leaving a 3 minutes gap between each run. The ones presented in figure 8, corresponding to sensor 3 in figure 1, are those whose pressure peak is closest to the mean peak of the 100 experiments. As for the lateral case, the mean of the pressure peak increases with the tank thickness, thus meaning the case cannot be considered in principle two-dimensional. The repeatability of the case, reflected in the standard deviation and Pearson coefficient is similar to the water lateral case of previous section, as can be observed in table III.

E. Roof impact oil

The dynamics is similar to the water roof impact case because air is not entrapped during the impact. This was not the case in lateral impact in which air was entrapped in the water case but not in the oil case. A sequence of images for each thickness is shown in figure 11. As can be seen, in the 0.5x case impact does not occur. For 1x case the the impact

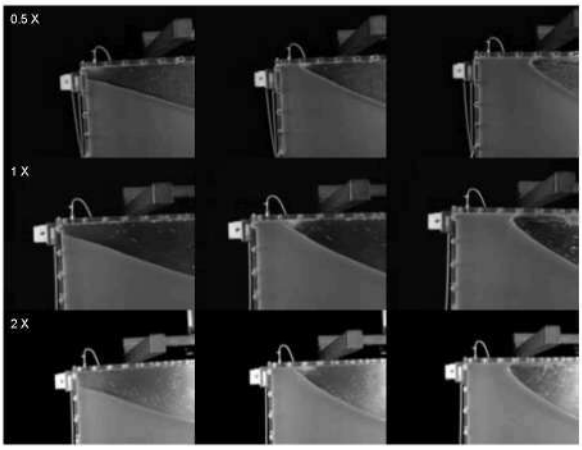


Fig. 9. Roof impact with water: Free surface shape during first peak event

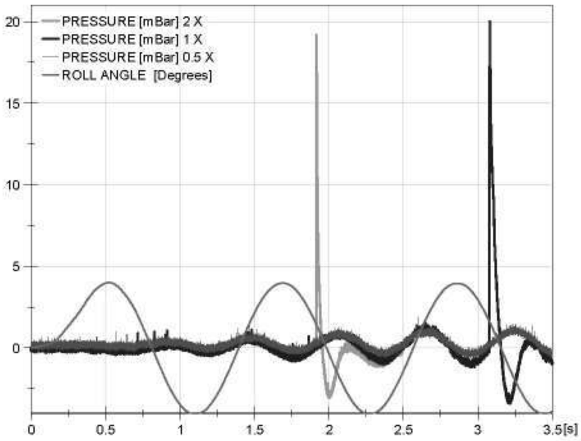


Fig. 10. Roof impact with oil: First peak pressure register

takes place after the second oscillation cycle, and for the 2x case the impact takes place after the first cycle. This in itself provides enough grounds to state that the case is not two-dimensional, which is confirmed by observing the pressure registers, shown in figure 10. The repeatability of the first pressure peak is significant though less evident than for the oil lateral impact, as can be noticed comparing the standard deviations and Pearson coefficients in tables III and II.

F. Next steps

The test case data will be improved in the next future by incorporating the following measurements plus eventually new ones after feed back from the SPH community:

1) Carry out measurement campaigns considering a range of intervals between consecutive measurements aiming at minimizing the dispersion of the impact pressure values for the first impact events.
2) Test thicker tanks and repeat measurements in order to find a configuration in which the pressure in the center plane can be considered independent of the tank thickness, which could indicate that the data is useful for validating $2D$ simulations. The effect of the development of turbulence prior to the impact in these assessments of two-dimensionality remains as well as a future challenge.
3) Modify cases configuration (period, amplitude, distance to the rotation center, etc...) to look for those with highest pressure peaks and repeatability.
4) Measure directly wave elevation.
5) Perform Laser Interferometry measurements of the flow velocity field.
6) Depressurize the tank in order to perform experiments with reduced ullage pressure.
7) Perform long measurements in order to provide statistical information about the peaks distribution, considering irregular motion of the tank as well.

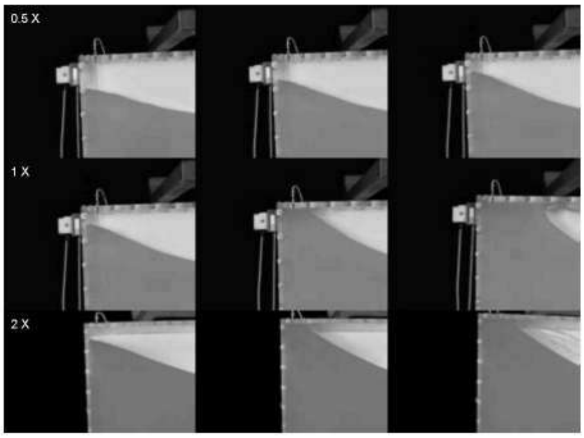


Fig. 11. Roof impact with oil: Free surface shape during first peak event

III. TUNED LIQUID DAMPING PROBLEM

A. General

The second proposed test case treats the coupling of the motion of a sloshing tank and a single degree of freedom structural system (SDOF), what is generally denoted as a tuned liquid damper (TLD). The tank is free to roll and its motion is excited by an externally created angular moment due to a periodically moving mass. It is a case of interest for mainly marine engineers interested in ship motions and for civil engineers using liquid dampers for mitigating the effects on large buildings and bridges from earthquakes and wind induced vibrations [11]. This proposed test case was used for validation in reference [12]. The aim of this test case is to show to what extent the breaking waves and sloshing dynamics affects the damping characteristics of a sloshing damper. SPH is a promising method for assessing the influence of wave breaking on the dissipation characteristics of a TLD, something that remains as a difficult challenge for conventional computational methods [13], [14]. To our knowledge there is no case covering such a topic in the SPHERIC database and there are limited cases in the literature specifically fit for numerical simulations and assessing the influence of viscosity.

The tank used for the experiments is the same as for the wave impact test case presented in section one, with the thickness 1X. This time the rotation center is 470mm above the baseline of the tank. The moment is induced by a mass $m = 4.978\,\mathrm{kg}$ that moves along an initially horizontal rail attached to the tank at the rotation center. The SDOF system will be described analytically and an abbreviated description of the experimental results of the coupling with the liquid motion will be presented.

B. SDOF model of the structure

An analytical model of the SDOF structural system used in the experiments is needed in order to have it incorporated into the structure part of the SPH code. It was obtained by measuring system masses and inertias and by analyzing its dynamics, in order to characterize its damping term, which is composed of a dry friction and a linear damping term. The analytical model used to describe the behavior of the system is described in equations 2 and 3.

$$\begin{aligned}\left[I_0 + m\xi_m^2(t)\right]\ddot{\phi} + 2m\xi_m(t)\dot{\xi}_m(t)\dot{\phi} - g\,S_G\sin(\phi)\\ + mg\xi_m(t)\cos(\phi) = Q_{damp}(t) + Q_{fluid}(t)\end{aligned} \tag{2}$$

$$Q_{damp}(t) = -K_{df}\cdot\mathrm{sign}(\dot{\phi}) - B_\phi\cdot\dot{\phi} \tag{3}$$

In these equation ϕ is the roll angle, g is the gravity, I_0, S_G are the polar moment of inertia and static moment of the rigid system with respect to the rotation center, $\xi_m(t)$, $\dot{\xi}_m(t)$ are moving mass position and velocity, K_{df} is the dry friction damping coefficient and B_ϕ the linear damping coefficient. Finally, $Q_{fluid}(t)$ is the fluid moment to be simulated with SPH. The values of these coefficients together with an assessment of the quality of the model investigated using free decay and forced motion empty tank tests have been included in [12].

C. Experimental results

The liquid depth (92mm) was chosen so as to match the first resonance period T_0 of the structural system. Cases at resonance, below and above, were considered for a range of mass motion amplitudes A. We describe briefly the case which offered the most relevant results, i.e., resonance one with $A = 100mm$ and refer the reader to the web link (http://canal.etsin.upm.es/ftp/SPHERIC_BENCHMARKS/) and to reference [12]. The indicator devised to characterize the damping effect of the liquid inside the tank is defined as 1 minus the ratio of the maximum amplitude of the roll angle in the partially filled and empty tank condition. The ratio ranges from a 76% reduction for water to 57% for glycerine, with oil in between. This can be appreciated from the time history of the tank motion from figure 12. The diverse liquid dynamics can be seen in figure 13, the water showing significant breaking, the oil, a much milder bore, and the glycerine almost a flat free surface, at the same motion instant ($t/T_0 = 8.66$).

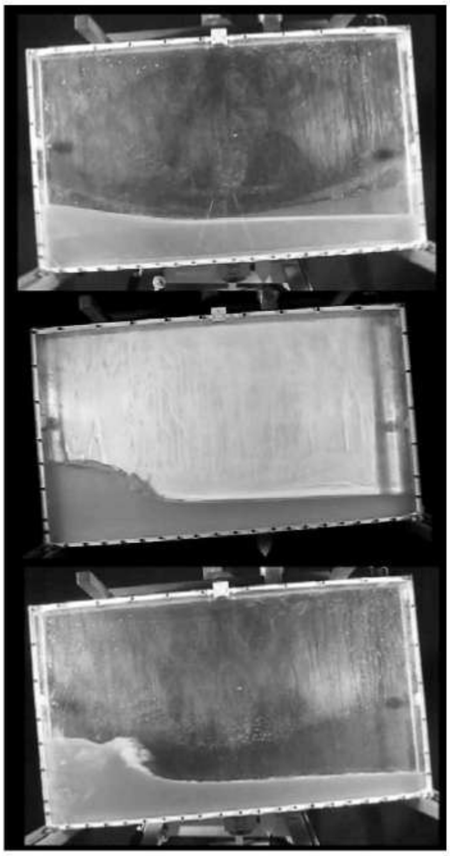


Fig. 13. Coupling problem: $A = 100mm$, $t/T_0 = 8.66$; glycerin (top), oil (middle), water (bottom)

D. Next steps

It seems the different breaking dynamics may be partially responsible for the different damping behavior for the three liquids considered. Nonetheless, accurately assessing this issue remains also as future work. The introduction of irregular excitations, baffles and other dissipation means may provide light into that difficult problem.

IV. Fluid Elastic Body interaction problem

A. General

In the literature, there are several comparisons between experiments and numerical solutions for FSI problems without free surfaces. Nevertheless, the combined case in which the fluid flow including the free surface motion interacts with deformable structures has not been well documented. With this motivation, the third proposed test case is a canonical fluid structure interaction problem. In reference [15], Antoci et al. presented an experiment consisting of a block of water breaking through an elastic gate. We have elaborated on their idea by looking for a strong interaction between a free surface sloshing flow in a rectangular tank where an elastic body is clamped in either the bottom or top center (figure 14). In order to make it more useful for CFD validation, the experiments have also been run with oil, thus covering a wider range of

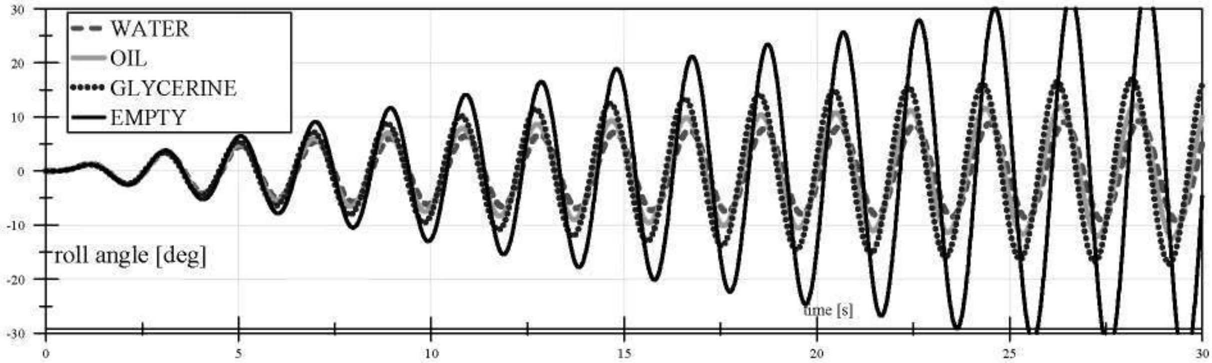


Fig. 12. Coupling problem: Roll angle time-history at resonance for $A = 100mm$

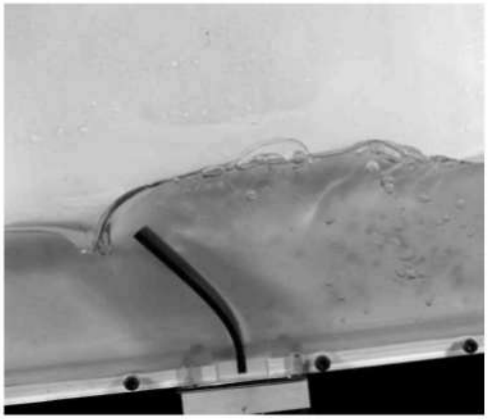


Fig. 14. FSI experiment with a free surface and an elastic body

Reynolds numbers. Preliminar results of this case have already been presented in [16] where they were used to validate a monolithic PFEM based FSI simulation and in [17] where they were used to validate the PFEM algorithm for a partitioned solution. We think this case could be a significant contribution to the SPHERIC test case database since FSI modeling is a crucial area of development of the SPH method.

The experiments of the present test case have been performed for a rectangular tank, similar but slightly smaller than the one used for the test cases of sections II and III. Either to the bottom or to the roof wall of the tank, an elastic beam may be clamped to interact with the fluid. The material properties of the beam probes, their dimensions and the properties of liquids (oil and water) are described in the information available online (http://canal.etsin.upm.es/ftp/SPHERIC_BENCHMARKS/) and in [16]. Similarly to Antoci et al. [15] experiments material, these rubbers present a viscoelastic behavior difficult to describe. The question to what extent are these complex material properties exhibited in the FSI experiments is not trivial. At the moment, they are considered negligible with respect to the complex dynamics of the FSI problem. However, rigorous answer to this question is an important task for the future work.

A quantitative comparison between experimental results and simulations is based on the measurment of displacements of specific points at the elastic beam from their original position, comprising at least the beam's tip. This displacement is measured in a local coordinate system of the tank. Three distinct configurations are considered, discussed briefly in the following sections. For more detailed information, we refer the reader to [16].

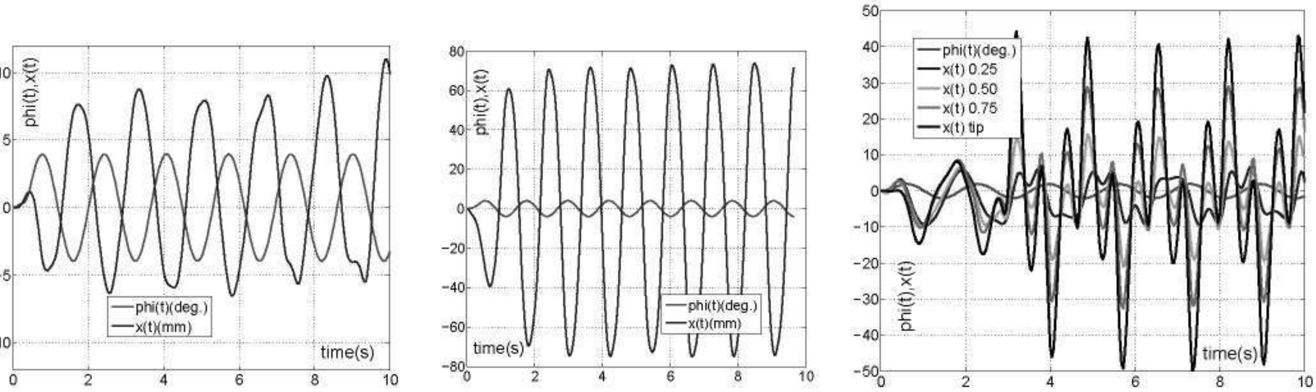
B. Experimental results

1) Clamped elastic beam immersed in a shallow and mid-depth oil: The first two experiments concern a clamped beam of different length immersed in sunflower oil. The bar length is exactly the same as the liquid depth which is 57mm in the first case and 114mm in the second one. Displacements of beam tip for both cases can be seen in figures 15(a) and 15(b).

2) Hanging elastic beam with shallow water: This is the most difficult case. The beam is hanging from the upper wall in such a fashion that the interaction with the fluid can be attained only due to the waves generated during the motion. Otherwise there is no interaction between the beam and the fluid, since the length of the beam (287.1mm) is supplemental with respect to the liquid depth (57.4mm) and the tank height. Since several deformation modes develop, the motion of the beam is described using the displacements of points at 0.25, 0.5, 0.75 of the beam length and its tip (figure 15(c)).

C. Next steps

This case is expected to evolve intensely in the near future. In wave impact problems, the interaction with the deforming container is crucial to assess the practical effects of peak pressure events. Since this case aims at serve as good validation tool for $2D$ codes, the $2D$ nature of the case will be assessed by studying deformations with thicker containers and a range of gaps. Like in the wave impact problems, it is important to perform PIV measurements of the velocity field together with wave elevation; it seems a lot of vorticity is shed from the bar tips onto the flow. A precise definition of the materials under analysis is also necessary for the future characterization of their viscoelastic behavior. Tests using materials with a



(a) Clamped beam immersed in shallow oil (b) Clamped beam immersed in mid-depth oil (c) Hanging beam with shallow water

Fig. 15. FSI: Roll angle and x displacement

linear elastic behavior (e.g. plexiglas bars) are also under consideration.

V. Conclusions

Three new benchmark test cases focusing on free surface flows have been presented, arising from the previous interests of the authors. The three new proposed test cases include a wave impact problem in a sloshing flow in a rectangular tank, the coupling of the angular motion of a sloshing tank and a single degree of freedom structural system and the interaction between a free surface sloshing flow and an elastic body. They incorporate, we believe, all the necessary information to implement them in SPH simulation codes, information which has been made available through the web link http://canal.etsin.upm.es/ftp/SPHERIC_BENCHMARKS/.

Although we aim at devising experiments with an essentially two-dimensional dynamics, related difficulties have been documented, mainly for the first proposed test case. As both SPH practitioners and experimentalists, we are committed to improving these test cases in the future. In order to achieve this, first, we try to simulate them ourselves, second, we hope to increase our experimental skills and capabilities, but mainly we ask for a feedback from the SPH community. Some of the future steps have been documented for each of the test cases, but hopefully new suggestions will arise from the use of these test cases by SPH practitioners.

Acknowledgment

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